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River stresses in anthropogenic times: Large-scale global patterns and extended environmental timelines

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Abstract:	Global perspectives on the complexities of environmental change impacts associated with past and present human activity are needed for food and water security challenges of the 21st century. This is especially true for rivers, for which the onset and persistence of a range in human activities, altering their function and form, have been temporally and spatially variable. Ancient civilizations, states and empires extended geographically to cover sub-continental areas where their river modifying activities became linked to regional Earth System stresses arising from climate and land use change. We present a new interpretative framework for characterising and classifying human impact on river systems, emphasising that this has taken place over decadal to millennial time periods on a sub-continental scale. This 16-element classification and documentation of different human transformations, including land management, urbanisation, industry and engineering activities, is used to explore anthropogenic channel and floodplain disruptions that have followed each other in different sequences in different places. It is significant that these inadvertent and deliberate human interventions have also taken place in parallel with contrasting climatic fluctuations that have been sub-continental in scale and varied in time. We assess the influence of the dominant modes of regional climate variability (monsoons, El Niño Southern Oscillation, Indian Ocean Dipole, North Atlantic Oscillation, Pacific Decadal Oscillation and Siberian High) on the speed and pattern of river system adjustment to anthropogenic perturbations. Some river civilizations have proved resilient to change given their adaptive management, while others have been overwhelmed by climate-related changes in river morphodynamics. We conclude that integrated socioeconomic, climatic and hydromorphological histories provide usefully instructive antecedents for sensibly managing, as they evolve, the even more serious coupled environmental stresses likely in the future.

Abstract

Global perspectives on the complexities of environmental change impacts associated with past and present human activity are needed for food and water security challenges of the 21st century. This is especially true for rivers, for which the onset and persistence of a range in human activities, altering their function and form, have been temporally and spatially variable. Ancient civilizations, states and empires extended geographically to cover sub-continental areas where their river modifying activities became linked to regional Earth System stresses arising from climate and land use change. We present a new interpretative framework for characterising and classifying human impact on river systems, emphasising that this has taken place over decadal to millennial time periods on a sub-continental scale. This 16-element classification and documentation of different human transformations, including land management, urbanisation, industry and engineering activities, is used to explore anthropogenic channel and floodplain disruptions that have followed each other in different sequences in different places. It is significant that these inadvertent and deliberate human interventions have also taken place in parallel with contrasting climatic fluctuations that have been sub-continental in scale and varied in time. We assess the influence of the dominant modes of regional climate variability (monsoons, El Niño Southern Oscillation, Indian Ocean Dipole, North Atlantic Oscillation, Pacific Decadal Oscillation and Siberian High) on the speed and pattern of river system adjustment to anthropogenic perturbations. Some river civilizations have proved resilient to change given their adaptive management, while others have been overwhelmed by climate-related changes in river morphodynamics. We conclude that integrated socioeconomic, climatic and hydromorphological histories provide usefully

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Keywords

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Introduction

The whole Earth System is now undergoing changes arising from global warming and wider human-induced modification (Steffen et al., 2011; Ellis, 2017). River channels and their floodplains are globally a critical Earth System element for human and ecosystem wellbeing as they impact on food and water security. Water-driven processes dominate land surface development for most of the habitable earth, so that spatial and temporal change trajectories are of considerable practical importance (James, 2017). For rivers and the alluvial environments alongside them, there is a need to better understand timings, interactions, trajectories and stabilities in relation to natural and anthropogenic perturbations of the Earth System (Macklin and Lewin, 2008). These have been less well established than the numerically defined and modelled trajectories postulated for the more rapidly responsive and recent atmospheric and oceanic ones now under way (IPPC, 2014). Whilst river adjustments to earlier conditions are evidently on-going, major *systematic* hydromorphic changes arising from global warming over the last half-century or so have yet to become evident. Such changes have arisen through the interactions of human and non-human agencies, the first mediated through the second. Together, they have combined to produce sequences of impact and change that we here call multiple river stress trajectories. Understanding river histories may help to anticipate, and therefore better to manage, the threatening and complex interactions across the globe that are likely to unfold in an Anthropocene future. Threats include extended drought periods and extreme flood episodes (Toonen et al., 2017). Channel dimensions and patterns relate to river discharge magnitudes, as driven by climate and modified by catchment transformations, so morphologies may be changed accordingly (Macklin et al., 2012b).

Some of the disturbances now evident are recent, with whole sets of human river-changing actions being near simultaneous during the 'Great Acceleration' since c.1950 (Steffen et al., 2014). Others, however, have occurred over centuries and millennia, and in different orders and combinations at particular sites (Lewin, 2013). For rivers, earlier environmental perturbations have conditioned later morphological adjustments, so that *temporal ordering,* and *time-dependent intervention technologies,* both matter. Every river catchment, and even every river reach, is in some way unique because of what has been done to it, and there have now been numerous smaller catchment studies illustrating in detail the course of human-influenced changes (Knox, 1977; Trimble, 1983; Dotterweich, 2008; Lewin, 2010; 2013; Foulds et al., 2013; Houben et al., 2012; Broothaerts et al., 2014; Fuller et al., 2014; Verstraeten et al., 2017).

In this paper we adopt a longer and larger temporal and spatial perspective, and present a new interpretative framework for characterising and classifying human impact on river systems worldwide over decadal to millennial time periods at a sub-continental scale. Through doing so, a deliberate attempt is made to match the global perspectives common to many Earth System studies for fluid atmospheres and oceans.

A basic premise also adopted is the long-standing geomorphological understanding, as outlined in many textbooks (Charlton, 2008; Knighton, 1998; Thorne et al., 1997), that river channel dimensions and channel patterns reflect the regime of water and sediment discharges fed into and through them. Change the balance between and amount of water and sediment input through climatic change or human catchment interventions, then channels also, over time, adjust. This includes channel expansion or contraction; changes from single to branching channel patterns; and aggradation or channel incision involving the dynamics of whole floodplains.

Discriminating anthropogenic timelines in river systems on a global scale

Figure 1 presents an 8-category historical global assessment of land occupation as mapped by Leszek Starkel (1987), based on the pioneering research of the eminent Russian botanist Nikolai Vavilov in the 1930s (Vavilov, 1951). To incorporate recent research, some areas have been updated, particularly in the Americas (Mann, 2005; Ellis et al., 2013; Ruddiman, 2014), and, since global regions are the focus here, the whole is re-plotted on a 2-hemisphere Mollweide equal-area projection. This approach summarizes a spatial history of land use: alternatives have been to model timings, rather than types, for the first 'significant' land use, both globally and in different biomes (Ellis et al., 2013), or to propose generalized pan-global sequence models (Ellis et al. 2017).

Land cover and cultivation practice are major factors in river sediment supply (Knox, 1977; Starkel, 1987); this in turn is a major determinant of channel pattern and floodplain sedimentation of rivers (Macklin and Lewin, 1997; Ashworth and Lewin, 2012). However, technologies of clearance, agriculture and management have varied considerably to produce sediment yield pulses of varying magnitudes (Xu Jiongxin, 2003; Dotterweich, 2008; Ellis et al., 2013; Macklin et al., 2014; Darby et al., 2016). In system terms, responses have been pulsed, lagged as well as ramped (Phillips, 2001; Poeppl et al., 2016). For example, European prehistoric, human-induced, alluvial sedimentation lagged behind initial forest clearance until more intensive activity and new plough technology came into operation (Stevens and Fuller, 2012; Broothaerts et al., 2014; Macklin et al., 2014). Hill slopes and floodplains appear initially not to have been well connected in terms of sediment transfer, with slope storages only feeding later on into river systems (Macklin et al., 2014; Verstraeten et al., 2017). Rapid Medieval population increase in Europe accelerated soil erosion, with more intensive cultivation using mould-board ploughing, but this phase was terminated by the Black Death (Kaplin et al., 2009). The Americas had landscapes ‘humanized’, in the sense of ecosystem change arising from anthropogenic activities, long before Columbian (post fifteenth-century) times brought in change of quite a different order (Deneven, 1992; Mann, 2005; Rooseveldt, 2013; Dotterweich et al., 2014). In the tropical Americas deforestation also succeeded a pre-European period of biomass destruction by fire followed by forest regeneration, so that ‘deforestation’ has not followed a simple trajectory (Nevle and Bird, 2008). Contemporary forest clearance in Amazonia now contrasts considerably in pattern, pace and technology with that of earlier eras elsewhere (Margulis, 2004).

As Phillips (2001) has argued, such historical and spatial contingency means that simple prediction of human impacts is not usually possible other than in strictly situational terms. For example, future channel bank erosion responses to changing flood regimes will manifest themselves in different ways (Lewin and Macklin, 2010).

Some floodplains now have long-standing deep blankets of post-settlement cohesive eroded soil materials (Macklin et al., 2014); others have been deprived of the resistance given by deep woody root systems (Gurnell, 2013). This means that riverbank resistances to flooding may now vary site by site according to what has been done to riparian vegetation and to bank cohesion.

In system terms, responses have also been pulsed, lagged as well as ramped (Phillips, 2001; Poeppl et al., 2016). For example, European prehistoric, human-induced, alluvial sedimentation lagged behind initial forest clearance until more intensive activity and new plough technology came into operation (Stevens and Fuller, 2012; Broothaerts et al., 2014). For the UK, Macklin et al. (2014) collated evidence of dated sediments that possessed evidence of anthropogenic content to demonstrate a lag between the development of agriculture in the Neolithic and accelerated river sedimentation. In Belgium and Turkey, hill slopes and floodplains appear initially not to have been well connected in terms of sediment transfer, with slope storages only feeding later on into river systems (Verstraeten et al., 2017). Mathematical modelling of such sediment transfers in the Rhine catchment involved dating and measurement of sediment produced by sheet and rill erosion, gullying and channel erosion, and then stored or depleted from slope and alluvial deposits (Hoffman, 2015; Naipal et al., 2016). Again, response patterns proved spatially and temporally variable.

These examples show that the effects of land use change on rivers are complex and mediated by inputs and outputs from sediment storages on hill slopes and floodplains over a millennial timescale. This is of considerable importance for the understanding of contemporary and future rivers that receive and transmit material activated by past land management – whether initially from Neolithic deforestation, medieval population increase and land pressure, colonial change, or the 'Great Acceleration' of recent decades.

Land management covers only one group of anthropogenic interventions affecting rivers: others follow from urbanisation, industrialization and the engineering of rivers and floodplains (Nilsson et al., 2005; Gregory, 2006; LeHooke et al., 2012; Tarolli and Sofia, 2016). These are summarized in Figure 2 (a-p), together with the inputs and modifications affecting river systems (A-H). Mediated through locally operating components of the Earth System, these then have produced river channel transformations, and frequently unintended ones: channel pattern change from multiple to single channels as documented in the UK (Lewin, 2010), river incision and entrenchment in the USA, Italy, Romania and the UK (Simon and Rinaldi, 2006; Downs et al. 2013; Macklin et al., 2013a; Rădoane et al., 2017), levee growth along the now laterally-stabilized Danube in Austria (Klasz et al., 2014), or the accelerated spillage of polluted and other sediment across floodplains as in the UK (Macklin et al., 2006; Foulds et al., 2014). River system changes, however, are not simply proportionate to changes in external driving forces (such as climate change and more frequent floods) since they are variably sensitive to them (Macklin et al., 2012b; Darby et al., 2016; Verstraeten et al., 2017). Effects of climatic variability on cultural change, and reverse feedbacks, have been far from straightforward in terms of chronological coincidence (Giosan et al., 2012; Weiberg et al., 2016). Transforming agents and local process responses have also both been uneven in space and time (Macklin et al., 2010; Benito et al., 2015).

With reference to urbanisation, megacities are overwhelmingly concentrated in Europe, parts of the Americas (in South America, mostly in coastal locations with minimal effect on river systems as yet), Southeast Asia, India, and now developing very rapidly in China within the last fifty years. Urban river transformations over centuries have primarily taken place within developing built-up areas themselves with reach-scale confinement. But they can also have downstream impacts notably through more flashy and higher runoff generated by paved surfaces and lined waterways, the dispersal of pollutants and the transformation of natural sediment dynamics (Chin, 2006). Luz and Rodrigues (2015) describe river changes in metropolitan Sao Paolo, Brazil from pre-disturbance conditions over some hundred years. A now-canalized river has been transformed, as has also the morphology and functioning of the floodplain. In urban areas, much also depends on bulk waste and sewage disposal technology, with minimal control in some developing world shantytown suburbs. This was equally true of Europe in medieval times, where rivers were used to disperse unwanted material as well as being used for power generation and for industrial processes such as leather tanning (Lewin, 2010), and particularly following the Industrial Revolution and the unconstrained use of rivers for waste disposal (Lewin, 2013). In the UK River Mersey system, coal dust and brick-making residues were fed directly into rivers in the eighteenth and nineteenth centuries in particular, as were human and animal waste. It is dominantly urban populations that now best get protected from floods and erosion through engineering structures, whilst watercourses have also constrained city layouts (Haur et al., 2016). Downstream rural environments have been less modified, but have paid a price in terms of the flooding and channel and floodplain pollution with toxic materials, as described above.

Civilizations have long histories of river and society co-evolution involving channel engineering (Macklin and Lewin, 2015). China probably has had the longest run of riverbank protection (since before the third millennium BCE; Zhuang and Kidder, 2014), and success in flood control on the Hwang He by the Emperor Yu is said to mark the start of Dynastic China (Wu et al., 2016). In Europe, channelization of the branching Danube came very much later in the nineteenth century, but it has led to river incision and levee sedimentation – each requiring time to develop in a particular context of other catchment changes (Hohensinner et al., 2013; Klasz et al., 2014). As well as on large rivers, channelization also affects small field drains that accelerate runoff from cultivated land, and larger rivers for navigation improvement.

Just a few major rivers were flow-regulated by dams in 1900 (trapping sediment and decreasing flood flow magnitudes). These were to be found in India, Europe and Brazil, but most were in the United States. By 1950 construction had greatly increased in these areas, but also in Southern Africa, Japan, and Australasia and with a few elsewhere. With a great acceleration after c.1960 especially in China, there is now considerable worldwide control, including run-of-river impoundments on nearly every major river, primarily for irrigation and power generation (Vörösmarty et al., 2003; Nilsson et al., 2005; Syvitski et al., 2005). To date the exceptions are Arctic rivers, together with the Amazon and the Amur. Whilst some flow regulation is in agricultural and part-urbanised catchments, others are in previously undeveloped (and often semi-arid) environments so that their impacts are different. River responses are likewise varied (Williams and Wolman, 1984; Petts and Gurnell, 2005), particularly depending on the sediment load being impeded.

Mineral extraction, with accompanying waste dispersal and downstream contamination, has similarly an extended history. Starting at a small-scale as early as 7000 years ago in the Middle East (Grattan et al., 2016), shifting and expanding to manufacturing areas proximal to the towns of the Industrial Revolution (Meybeck, 2003), and then in the colonial era affecting catchments in the Global South distant from prospering urban manufacturing centres in Europe and North America (Hudson-Edwards et al., 2001).

With all these activities – agriculture, urbanization, industry and river engineering – the technologies used, the relative order of their deployment, and the combinations involved were vital for establishing the nature of riverine environment transformation. For example, forest clearance today, using heavy equipment, laser levelling of fields, and monoculture is very different from ancient or medieval techniques. Upstream industrial pollution coming largely *after* flood protection in the Netherlands has meant that resultant land quality deterioration has been area restricted (Middelkoop, 2000). In catchments with limited or no flood management, contaminant dispersal has occurred across entire floodplains (Macklin et al., 2006; Foulds et al., 2013), to be left in place as historically contaminated land that is often unrecognised by farmers and environmental managers behind protected riverbanks (Macklin et al., 2006). In the UK, waterpower initiated the Industrial Revolution, so both industrial and urban pollutants were fed into small rivers that already had numerous milldam pools and navigation weirs along channels where pollutants accumulated (Lewin, 2013).

Figure 3 provides seven summary timelines for major world rivers or regions that are representative of global land-occupation categories (Figure 1) and that have well-documented river histories. Bars represent the time periods during which anthropogenic river-modifying activities (summarised in Figure 2) have been effective. Each plot shows a unique ‘imprint’ of deliberate and inadvertent human impact that conditions river system susceptibility to present and future environmental stress. As Edgeworth et al. (2015) have pointed out, the lower sedimentary bounding surface for what they call the ‘archaeosphere’ (the boundary for anthropogenic deposits) is diachronous, and this applies equally to each one of the human activity inputs, which vary between different rivers (Phillips, 2001). The plots themselves are intentionally regional overviews, and detailed research is required on a reach-to-catchment scale in order to spatially and temporally constrain land management, urbanization, industry and engineering timelines (Rădoane et al., 2017). In reality all of these factors vary: the local resilience of flood control structures (Chen et al., 2012), the intensity of cultivation (Naipal et al., 2016), and the efficiency of sediment trapping by impoundments (Vörösmarty et al., 2003). But overall, there are situational contrasts clearly apparent between each of the long-developed areas (Hwang He, Nile and Central Asia), including pauses and hiatuses in occupation (Stevens and Fuller, 2012; Dotterweich et al., 2014; Macklin et al., 2014). Other regions have only relatively recently been subject to major engineering control (as in the United States and New Zealand) and catchments have had different land management histories (Downs et al., 2013; Fuller et al., 2015). European rivers, as in the UK, have extended management and urban legacies together with river engineering to the extent that few rivers, large or small, are now without some form of management such as bank protection or dredging (Lewin, 2010; 2013; Downs et al., 2013; Habersack et al., 2014). It is important to note that change is not all one-way: for example, medieval soil erosion in England has been followed by stabilization such that sediment yields may now be dominated river bank rather than hillside inputs (Pulley and Foster, 2016).

Precise forecasting of future river change in these contexts via physical or numerical modelling of ‘natural’ channels is not as straightforward as documenting evidence for what is now known to have happened. Lewin and Brewer (2001) showed that generally available data sets for stream power and channel pattern (braided or meandering) do not show simple relationships without dubious manipulation. Quantified but variable bank resistance is likely to be a significant missing factor, and one much affected by local anthropogenic influence. Probable change rates for future lateral bank erosion or sedimentation responses are also difficult to quantify given only short timespan measurements for already part-transformed situations (Kessler et al. 2013; Pulley and Foster, 2016). Change may further be accomplished through channel abandonment (Macklin and Lewin, 2015), incision or aggradation, and the pulsed movement of sediment slugs (Nicholas et al., 1995), whilst overbank sediment and sediment-associated contaminant dispersal is greatly influenced by disruption of sediment distributary system connectivity (Lewin and Ashworth, 2015). Connectivity as a concept applies equally to downstream sediment dispersal as to upstream input and transport (Hoffmann, 2015; Poeppl et al., 2016; Bracken et al., 2015; Verstraeten et al., 2017).

Ⅲ Discriminating hydroclimatic timelines of river systems on a global scale

Although there have been several recent attempts to globally map and model past and possible future land use changes (Ellis et al., 2013), the spatially variable impacts of climate fluctuations on rivers affected by anthropogenic change have not been systematically evaluated. Regionally fluctuating hydroclimates are likely to have been equally as important in steering the dynamics of hydromorphic regimes as have the inadvertent or deliberate human impacts discussed so far. In particular, this is because river channel morphology and size are critically dependent on climate via water runoff and the sediment delivery brought about through vegetation change response to aridity or increased precipitation as well as direct cultivation. Thus the patterns and speed of river adjustment to anthropogenic perturbations is paced by climate-related shifts in hydrological extremes (floods and droughts). This is most clearly manifested by the relationship between river flows, floods and the dominant modes of regional climate variability (notably monsoons, the El Niño Southern Oscillation [ENSO] and the North Atlantic Oscillation [NAO]) that result in hydromorphic changes over decadal, multi-centennial and sometimes longer timescales (Macklin et al., 2012b). To explore how large-scale and long-term climate-related stress-coupling trajectories intersect with anthropogenic interventions in river systems, Figures 4 and 5, respectively, plot global monsoon domains (Wang et al., 2012) and the spatial extent of hydroclimatic influence of the principal high-frequency climate modes – ENSO (Dai and Wigley, 2000), NAO (Osborn et al., 1999; Cullen et al., 2002; Zhang et al., 2010), Pacific Decadal Oscillation (PDO) (Mantua et al., 1997; MacDonald and Case, 2005; Goodrich and Walker, 2011), Siberian High (SH) (Gong and Ho. 2012), and the Indian Ocean Dipole (IOD) (Marchant et al., 2006). Holocene summary timelines (Figure 6) have also been constructed for these dominant modes of global climate variability.

All large African (Congo, Niger, Zambesi), Indian subcontinent (Indus, Ganga, Brahmaputra-Jamuna), and Southeast Asian (Irrawaddy, Mekong, Yangtze, Hwang

He) rivers have flow regimes controlled by the monsoon. In South America only the southernmost rivers (Uruguay and Rio Negro) have hydrologies unaffected by monsoonal rainfall. Overall, in more than half of the world's largest rivers a monsoonal flow regime predominates, with an estimated 60% of the world’s population directly affected by the Asian Monsoon (AM). The climatic trajectories of monsoon-influenced rivers in the Northern and Southern Hemisphere have however differed during the Holocene, especially those in South America (Figure 6). The AM shows a long-term decline from c.7 ky B.P. following summer insolation (Donges et al., 2015), punctuated by multi-centennial periods of significantly lower and more variable rainfall centred at 8.3, 7.2, 6.3, 5.5, 4.4, 2.7, 1.6 and 0.5 ky B.P. (Figure 6), many of which (at 8.3, 4.4, 2.7, 1.6, and 0.5 ky B.P.) coincided with Bond events (Bond et al., 2001) and cooler conditions in the North Atlantic. In addition, there are non-linear regime shifts to a weaker Asian Monsoon at 8.5-7.9, 7.5-7.2, 5.7-5, 4.1-3.9 and 3-2.4 ky B.P (Donges et al., 2015). Similarly major weakening of the African summer monsoon in the Northern Hemisphere, as reflected in reduced Nile floods and associated with channel and floodplain contraction, is recorded at 8-7.6, 6.4-6, 5.7-5.3, 4.7-4.2, 3.3-2.9, 2.8-2.5 and 0.4 ky B.P (Macklin et al., 2015).

There is evidence for a north-south hemispheric synchrony of Holocene climate change in tropical Africa, with rapid aridification events beginning both regions at c. 3.5 ky B.P. (Chase et al., 2010). A long-term trend of progressive aridification over the last 3000 years has been recognised throughout the northern tropics (Asia, India, Africa and northern South America) as well as in southern tropical Africa. Abrupt multi-centennial periods of reduced precipitation are linked to the North Atlantic meridional overturning circulation with a slowdown associated with freshwater pulses in the Northern Hemisphere. South American speleothem records (Strikis et al., 2011) show increased precipitation centred at 9.2, 8.2, 7.4, 7, 6.6, 5.2, 4, 3.2, 2.7, 2.3, 2.2 and 1.9 ky B.P., with the strongest events at 8.2 and 4 ky B.P. The South American Monsoon (SAM) has an anti-phase relationship with AM precipitation, with low rainfall over eastern China at 9.2, 8.2, 7.4 and 3.1-2.7 ky B.P. (Donges et al., 2015) coinciding with intensification of SAM (Strikis et al., 2011).

ENSO's influence on river regime encompasses the whole of the Americas, Southern (Ganga, Brahmaputra-Jamuna) and Southeast Asia (Irrawaddy, Mekong, Yangtze, Hwang He), Western (Niger), equatorial (Congo, Nile) and Southern Africa (Zambezi, Limpopo, Orange), and southeast Australia (Murray-Darling). Significant increases in the frequency and intensity of ENSO are evident in the early Holocene (11.5-9.0 ky B.P.) but also at 4.2 and notably 2.0-1.5 ky B.P. (Conroy et al. 2008; Gouramanis et al., 2013).

The NAO and SH represent the major modes of climate variability in the Northern Hemisphere. The NAO influences river regimes in western (Danube, Tigris-Euphrates) and eastern Eurasia (Brahmaputra-Jamuna, Irrawaddy, Mekong, Yangtze, Hwang He) as well as eastern North America (Rio Grande, Missouri-Mississippi, Saint Lawrence) although proxy records at present only extend as far back as 5.2 ky B.P. (Olsen et al., 2012). The periods between 5.0-4.55 and 2.0-0.55 ky B.P. were characterised by predominantly NAO^+ circulation patterns, whereas frequent periods of mainly NAO^- circulation are recorded between 4.5-2.0 and 0.5-0.15 ky B.P. The SH is the major control of hydroclimate over multi-decadal to multi-centennial timescales in northern (Volga, Ob, Yenisei, Lena), central (Amu-Darya and Syr-

Darya) and eastern Eurasia (Amur, Hwang He, Yangtze). Periods with stronger SH are recorded at 8.9-8.0, 6.1-5.0, 3.2-2.4, 0.65-0.15 ky B.P. (Mayewski et al., 2004). These are associated with increased flooding in northern (Benito et al., 2015) and central (Olsen et al. 2012) Eurasia resulting from enhanced snowmelt, but drought in the monsoon-influenced rivers of eastern Eurasia.

The Pacific Decadal Oscillation (PDO) is the leading mode of multi-decadal and longer-term hydroclimatic variability in the extra-tropical north Pacific and North America more generally (Mantua et al., 1997; MacDonald and case, 2005). The warm phase of the PDO (+ mode) has a similar hydroclimatic influence as El Niño, and the effects associated with its cold (-) phase resemble those of La Niña (Goodrich and Walker, 2011). For North America this results in south-west rivers (Colorado, Rio Grande) being out of phase with those in the north-west (Columbia, McKenzie, Yukon), the central area (Missouri-Mississippi) and the eastern Atlantic seaboard (Saint Lawrence). Warm (+) phase PDO corresponds with higher river flows in the southwest, and cold (-) phase PDO is associated with drought in the Southwest, but wetter conditions in all other regions of the USA (Conroy et al., 2008). The early Holocene (9.7-8.85 ky B.P.), mid-to-late Holocene (4.8-3.2 ky B.P.) and the latest Holocene (1.5-0.15 ky B.P.) define three generally positive PDO intervals (Figure 6) with wetter conditions and higher river flows in the American Southwest (Kirby et al., 2010). By contrast, much of the interior of North America has been dry during cold (-) phase PDO.

The IOD has traditionally been viewed as an artefact of the ENSO system but increasingly evidence is amassing that it is a separate and distinct phenomena

(Gouramanis et al., 2013). In its negative phase wetter conditions are found in parts of Southeast Asia, most notably the Mekong and in southern and eastern Australia, including the Murray-Darling basin. Periods of positive IOD are characterised by wetter conditions over the Indian subcontinent (Indus, Ganga, Brahmaputra-Jamuna) and southern parts of the Yangtze basin. A more positive IOD-like mean state appears to have existed before 6.8 ky B.P. and between 5.5-4.3 ky B.P. (Abram et al., 2009).

Anthropogenic and hydroclimatic stress-coupling trajectories of global rivers

By comparing long term anthropogenic environmental change timelines of river systems (Figure 3) with Holocene timelines for dominant modes of climate variability (Figure 6), an assessment can be made as to whether hydroclimatic ‘shocks’ had a discernible impact on human activity (land management, urbanisation, industry and river engineering practices), and whether anthropogenic actions amplified or attenuated climatic signals in local rivers.

The Hwang He and Nubian Nile – monsoon-controlled rivers – have been differently impacted by hydroclimatic fluctuations even though farming and irrigation both developed in the 5th and 3rd Millennium BCE, respectively. The adoption of agriculture in both regions falls within periods not marked by large-scale changes in monsoon dynamics. However, the development of large-scale irrigation coincides with reduced flows associated with weaker Asian and African monsoons. Although the Hwang He has experienced six multi-centennial periods of weak monsoon and low rainfall since the establishment of agriculture c. 7 ky B.P. (Donges et al., 2015), societies there have remained doggedly resilient to climatic variability despite huge human losses during both major floods and droughts (Davis, 2000). Indeed, the founding of dynastic China coincided with successful control of large-scale flooding at c.1900 BCE (Wu et al., 2016). Construction of the first major reservoirs at c. 2.6 ky B.P. similarly corresponds with an extended period of low rainfall. Irrigation agriculturists in the Nubian Nile, however, despite coping with multi-centennial periods of reduced Nile flow at 4.7-4.2 and 3.3-2.5 ky B.P., abandoned much of the Nile Valley between the Second and Fourth Cataracts at 1.6 ky B.P. (coinciding with a phase of intense El Niño centred at 1.5 ky B.P.) until the middle of the 20th century (Macklin et al., 2013). In both regions climate change resulted in river transformation – flood-related avulsion in the Hwang He (Chen et al., 2012) and drought-related channel and floodplain contraction in the Nubian Nile (Macklin et al., 2013b) – as hydromorphic thresholds were crossed. Societal responses to these were entirely different with increasing engineering solutions and continued population growth in the Hwang He (Chen et al., 2012; Kidder and Zhuang, 2015), contrasted with the collapse of floodwater farming and depopulation in the Nubian Nile, starting at c. 3.2 ky B.P. (Macklin et al., 2013b; 2015).

Farming and irrigation-based cropping in Central Asia beginning in the 5th and 3rd millennium BCE, respectively, resulted in anthropogenic timelines in Amu- and Syr-Darya catchments virtually identical to those in the Hwang He and Northern Chinese Plain (Figure 3). This is notwithstanding the fact that river hydrology in Central Asia is primarily controlled by precipitation from westerly air masses whose penetration into the Eurasian landmass interior is determined by the strength of the SH. These catchments also show no evidence for disruption of human activity that impacted on river dynamics during periods when the SH strengthened at 6.1-5.0, 3.2-2.4, 0.65-0.15 ky B.P. (Mayewski et al., 2004). The development of large-scale irrigation in the region at c. 4.4 ky B.P. occurred during a weak phase of the SH. A stronger SH has been shown to be associated with higher Aral Sea water levels and river flows in Central Asia (Macklin et al., 2015b; Panyushkina et al., 2018) and it is likely that the adoption of irrigation in the mid-3rd millennium BCE was prompted by a decrease in water supply, especially in the lower reaches of the Amu- and Syr-Darya catchments. This pattern was repeated in the second half of the 1st millennium BCE with the initiation of river engineering and canal construction in the Aral Sea region (Adrianov and Mantellini, 2013). There is a very notable c. 600 year long hiatus, from the early 13th until the 19th century, in urbanisation impacts (sewage and runoff) on river systems in Central Asia resulting from the widespread destruction of cities (e.g. Otrar, 1219) in the region by Genghis Khan and his armies.

As the consequence of differences in the timing and nature of European contact and colonisation, and the early industrialisation of the UK (Figure 3), river systems in the UK, Mississippi, Southwest USA and New Zealand have very distinct anthropogenic timelines. In the New World impacts of climate fluctuations in the form of multi-centennial length ENSO and PDO phases, are evident in the pre-Columbian Mississippian (Munoz et al., 2015) and American Southwest (Nelson et al., 2010) riverine societies in the period 0.8-0.4 ky B.P. Major floods in the Mississippi and extended droughts in the SW USA were linked with migration and widespread settlement abandonment (Kidder et al., 2008; Munoz and Gajewski, 2010; Nelson et al., 2010). In smaller dryland rivers of the American Southwest during this and in earlier periods of climate change, geomorphological thresholds were crossed in major floods with channel entrenchment and the development of arroyos (Waters et al., 2001; Harden et al., 2010). The increased frequency of severe floods in the

Mississippi catchment c. 0.8-0.3 ky B.P saw major expansion of the floodplain though without hydromorphic transformation. This was, however, sufficient to cause a complete reconfiguration of lifeways in the Mississippi-Ohio river valleys (Munoz et al., 2015).

The UK and New Zealand constitute end members of anthropogenic and environmental timelines characteristic of mid-latitude river systems globally. Land management for farming (c. 6.1 ky B.P.), building construction (c. 3 ky B.P.) and mineral extraction (c. 4 ky B.P.) have affected most of the UK for millennia. The world's first industrial nation produced some unique anthropogenic modifications of river environments (Lewin 2010; 2014) resulting from settlement and industrial and mining wastes (Macklin et al., 2014). By contrast, New Zealand is the world's most recently settled major landmass (< 800 years). With large-scale European colonisation and immigration not taking place until 1840, gold mining in the late 19th century and with limited urbanisation and industrialisation during the 20th century (a trend that is largely continuing in the early 21st century), its anthropogenic and environmental change river timelines are globally distinctive (Fuller et al., 2015; Clement et al., 2017). Holocene climate change has had a significant impact on river environments and dynamics in both the UK (Macklin et al., 2010) and New Zealand (Richardson et al., 2013) manifested by changes in the frequency and magnitude of large floods controlled by NAO phase in the North Atlantic and ENSO/PDO in the Southwest Pacific (Macklin et al., 2012a). Hitherto, Holocene hydroclimatic fluctuations in both regions have not been of sufficient magnitude to result in climatic shocks or stresses large or long enough to result in major discontinuities or extended disruptions in the human use of river environments. But in the UK, especially over the last 1000 years, river transformations have increasingly emerged from the interaction between human activity and hydroclimatic fluctuations (Macklin and Lewin, 1993; Macklin et al., 2010; 2013a; 2014).

It is notable that during the pre-industrial period, with the exception of the Hwang He, all regions and major rivers we have assessed have multi-centennial length discontinuities in anthropogenic environmental change timelines that affected river processes and environments. These arose from hydroclimate shifts (Nubian Nile c. 1.6 ky B.P., Mississippi and SW USA c. 0.8 ky B.P.), social and cultural change (UK c. 4.8 and 1.6 ky BP), disease (North America c. 0.5 ky B.P.) and warfare (Central Asia c. 0.8 ky B.P.). The Hwang He stands alone, not only as the first major world river to be anthropogenically transformed, but also to be continuously affected by human activity for more than 7,000 years. Nevertheless, taking a long view and a global viewpoint, its riverine societies have been remarkably resilient. Anthropogenic climate change is rapidly becoming much more significant than the climate variability of earlier periods in the Holocene (Fig. 6), but future impacts on individual global rivers are very difficult to predict for reasons that have been outlined above. However, given that the majority of rivers and their floodplains in the more densely populated parts of the world were engineered during a climatically benign 20th century, the future coupling of environmental and civilizational stress is likely to be at best challenging and at worst catastrophic in the sense of disrupting present ways of life entirely.

Conclusions

A conclusion must be that, in addition to defining a new global epoch or geological era in which anthropogenic effects are paramount (Zalasiewicz et al., 2010), it is desirable to disaggregate the global contextual histories and regional susceptibilities of rivers to environmental perturbations, as has been done for changing land cover (Ellis, 2011; Ellis et al., 2013; Pelletier et al., 2015). Major changes are yet to come, but rivers of ‘the present’ are not in a pristine state but rather are ‘prepared’, part-managed, geographically complex, and variably susceptible. A non-pristine state was true of the United States even in 1492 (Deneven, 1992) as well as having been the case in China and Europe for millennia (Zhuang and Kidder, 2014; Macklin et al., 2014). Continental catchments act as discrete units, episodically integrating multiple effects produced by larger scale physical and social changes, with earlier events and system transformations constraining later phases of morphodynamic readjustment lasting centuries.

This contrasts with the wide global reach and limited ‘memory’ effects underlying atmospheric change. Such global change does, of course, greatly impact catchments systems, and it will do so in years to come to a much greater extent as an unintended consequence of fossil fuel consumption. But climate change also has varied manifestations globally, including its impacts on river systems. Coupled with conditioning by past and often quite variable human activities on a local-to-regional scale, this has created a global patchwork of change and stress on rivers and floodplains. For practical understanding to emerge, this patchwork needs to be understood globally as well as on a reach-to-catchment scale. In the context of hazard and river management, we should not be driven by simple visions of a single worldwide past or future threshold or sequence for environmental change.

In effect, this viewpoint takes a particular conceptual position following an interpretation of a considerable volume of existing research. It supplements, but contrasts with, efforts to define a new global Anthropocene with a start date of c.1950 (Steffen et al., 2011). Our approach is not one of identifying an onset timing for supposed human dominance, but one of exploring a long history of interactive, multi-element evolutionary change − including both climatic and deliberate/inadvertent human agency. In short, the case is made for favouring composite and extended timelines rather than periods. Furthermore, such are the permutations of society and climate histories across the globe, and the varieties of river response, that no single riverine evolution model applies. Managing future transitional and transformational phenomena, with planetary ways of living evolving at least on a multi-decadal to centennial timescale, should involve developing a range of practicable local policies and interventions across the globe, targeted to take account of human heritage forms and variable hydroclimate stresses at sub-continental levels.

Data availability statement

All data generated or analysed during the current work are available from the corresponding author on reasonable request.

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Figure captions

Figure 1. Global land-occupation categories after Vavilov (1951) and Starkel (1987), with additions and updates by the authors. The map shows areas of ancient agriculture (some abandoned and then developed again more recently; a-d), those developed in the last two centuries (e and f), and ones that have been little affected by human activities until the mid-20th century (g).

Figure 2. Human activities leading to fluvial responses via input modifications to the Earth System. Based on concepts from various sources (Syvitski et al., 2005; Chin, 2006; Macklin et al., 2006; Dotterweich, 2008; Lewin, 2010; 2013; Downs et al., 2013; Ellis et al., 2013; Foulds et al., 2013; Rădoane et al., 2017). Human activities (a-p) have been variously timed and have often occurred simultaneously. These lead to a range of river modifications through material inputs, controls and discharge

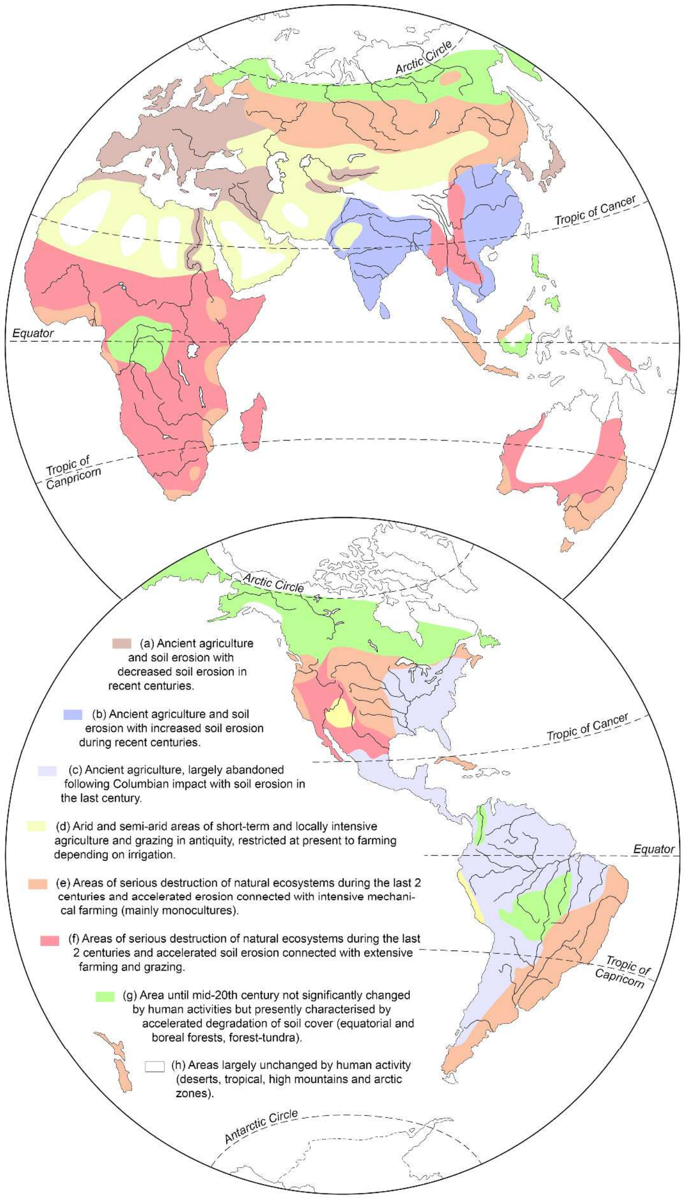
changes (A-G), in conjunction with anthropogenic atmospheric change (H) that results in alteration of the frequency and magnitude of extreme hydrological events (droughts and floods). Working through functioning earth systems, this leads to a range of river channel and floodplain responses (1-3).

Figure 3. Seven sets of anthropogenic timelines for major world rivers or regions that are representative of global land-occupation categories shown in Figure 1 and have well documented river histories. Bars represent the time periods during which the river-modifying activities represented in Figure 2 have been effective. No two areas have had the same history, whilst future responses to climatic change will equally be differently constrained. Sources are as follows: Hwang He - Chen et al., 2012; Highham 2013a; 2013b; Zhuang and Kidder, 2014; Kidder and Zhuang, 2015; Wu et al., 2016; Nubian Nile - Woodward et al., 2001; 2017; Macklin et al., 2013b; 2015; Central Asia - Lewis, 1966; Chang, 2012; Krivonogov et al., 2014; Macklin et al., 2015; Panyushkina et al., 2018; UK - Lewin 2010; 2013; Macklin et al., 2010; 2014; Stevens and Fuller, 2012; Mississippi - Deneven, 1992; Knox, 2006; Kidder et al., 2008; Munoz and Gajewski, 2010; Munoz et al., 2015; Peros et al., 2014; SW USA - Bayman, 2001; Waters and Ravesloot, 2001; Harden et al., 2010; Nelson et al., 2010; Huckleberry et al., 2013; 2014; and New Zealand - Macklin et al. 2014; Richardson et al. 2013; 2014; Fuller et al., 2015; Knight, 2016; Clement et al., 2017.

Figure 4. Global monsoon (Wang et al., 2012) and principal high-frequency hydroclimate mode domains in the Northern Hemisphere: ENSO (Dai and Wigley, 2000); NAO (Osborn et al., 1999; Cullen et al., 2002: Zhang et al., 2010); Pacific Decadal Oscillation (PDO) (Mantua et al. 1997; MacDonald and Case, 2005; Goodrich and Walker, 2011); and Siberian High (SH) Gong and Ho, 2012). Shaded regions in North America delimit areas and major rivers that experience high precipitation during positive (warm) phases of PDO.

Figure 5. The influence of ENSO (Dai and Wigley, 2000; Hoerling and Kumar, 2000; Ropelewski and Halpert, 1987) and the Indian Ocean Dipole (Gouramanis et al., 2013) on global precipitation and temperature patterns. El Niño and La Niña phases shown in the left and right panels, respectively.

Figure 6. Holocene timelines for dominant modes of global climate variability: Asian (Donges et al., 2015), African (Macklin et al., 2015) and South American (Strikis et al., 2011) Monsoons; El Niño Southern Oscillation (Conroy et al., 2008); Pacific Decadal Oscillation (Kirkby et al., 2010); North Atlantic Oscillation (Olsen et al., 2012); and Siberian High (Mayewski et al., 2004).



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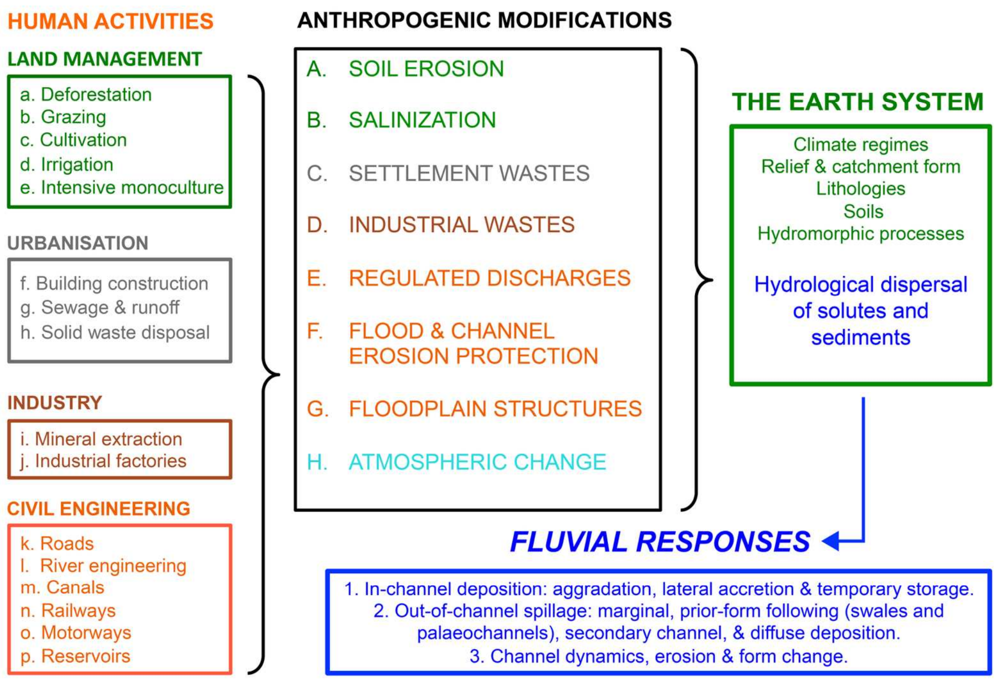

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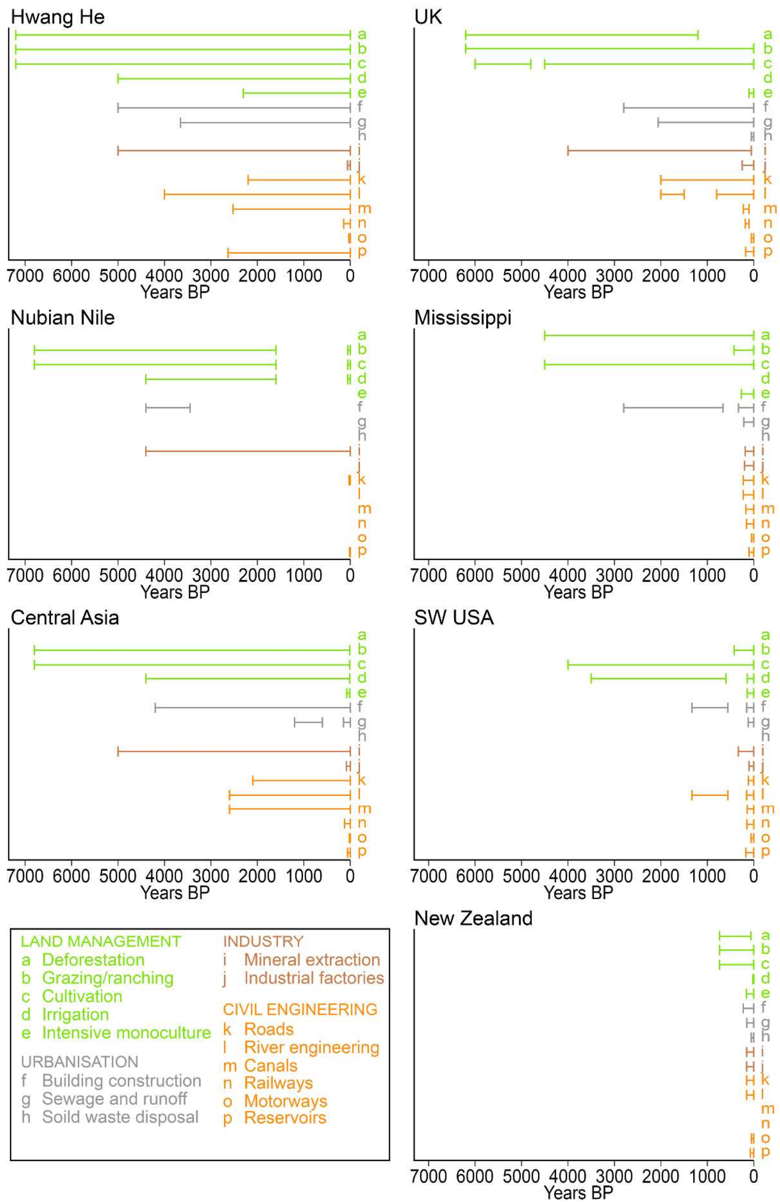

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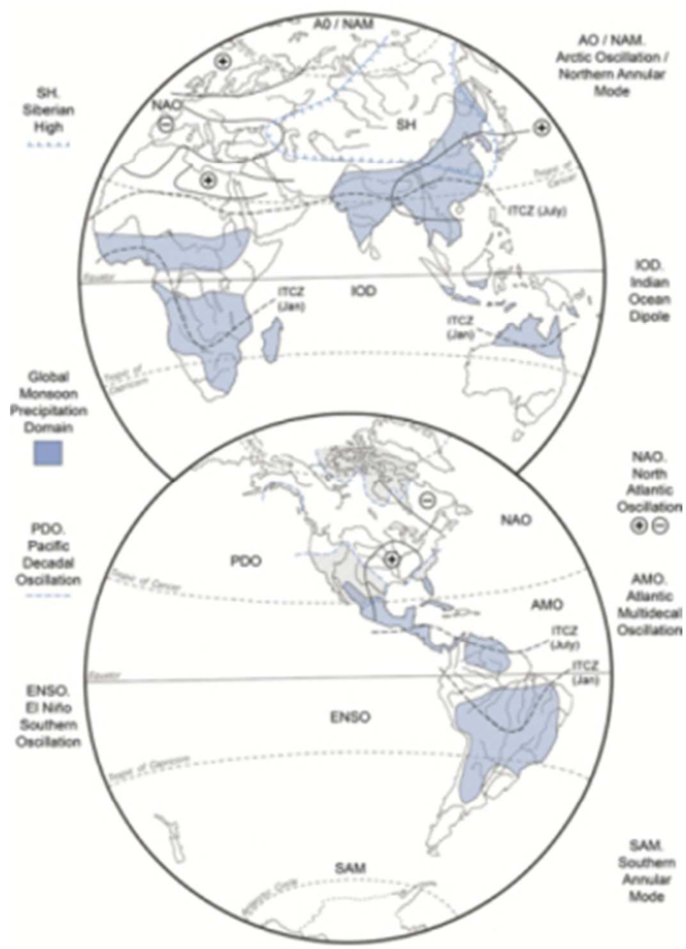

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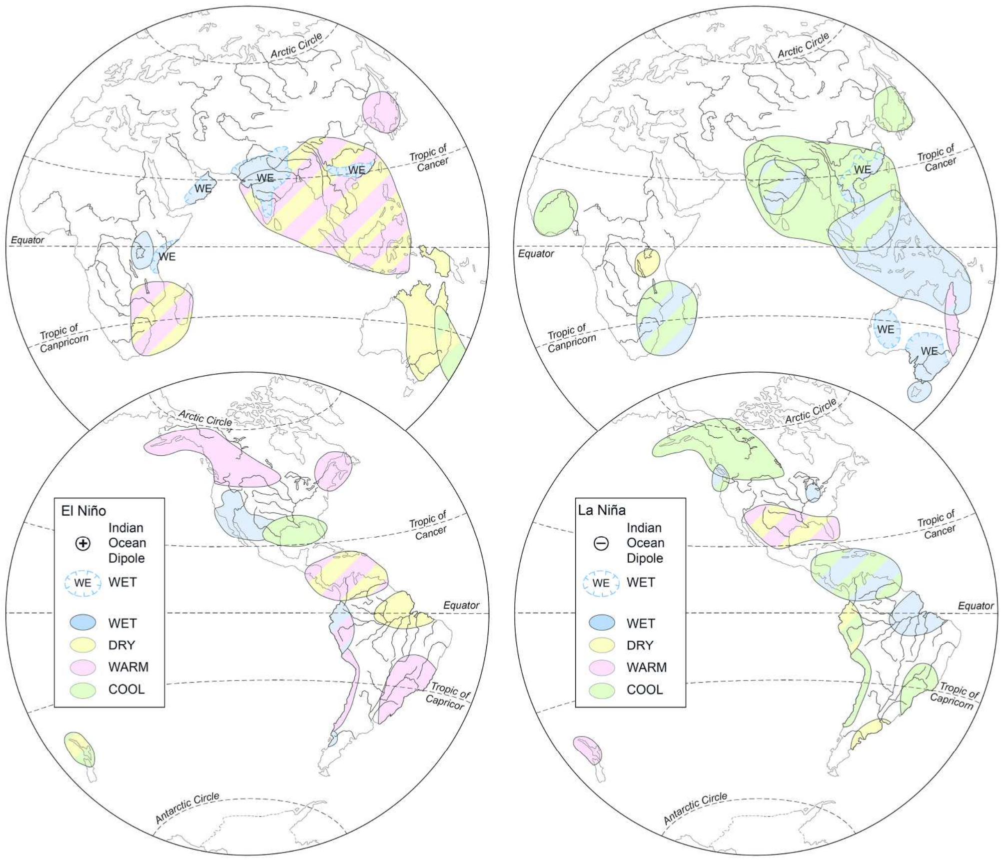

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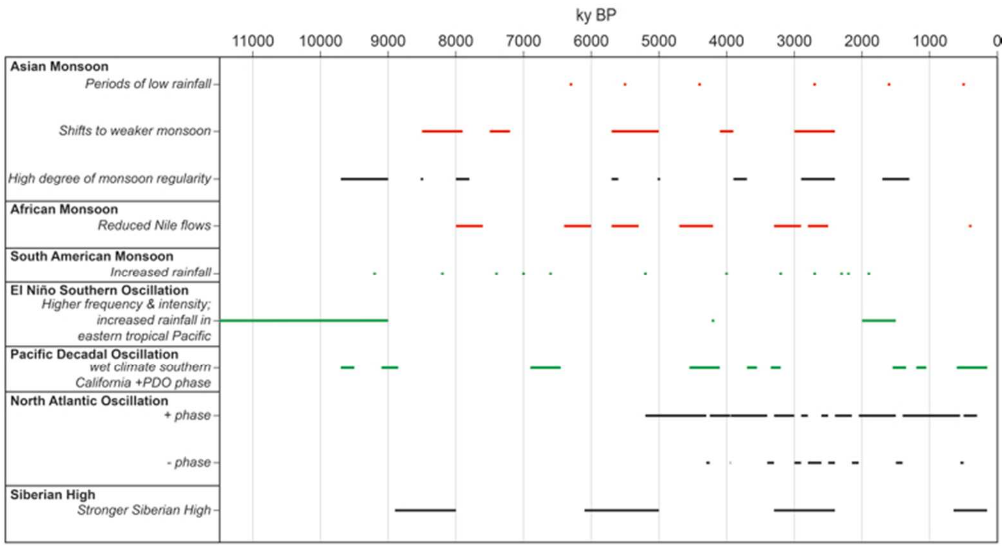

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